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Effects Of Oil On The Rate And Trajectory Of Louisiana Marsh Shoreline Erosion

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Effects of oil on the rate and trajectory of Louisiana marsh shoreline erosion

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Effects of oil on the rate and trajectory of Louisiana marsh shoreline erosion

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Abstract

Oil can have long-term detrimental effects on marsh plant health, both above- and belowground. However, there are few data available that quantify the accelerated rate of erosion that oil may cause to marshes and the trajectory of change. Between November 2010 and August 2012, we collected data on shoreline erosion, soil strength, per cent cover of *Spartina alterniflora*, and marsh edge overhang at 30 closely spaced low oil and high oil sites in Bay Batiste, Louisiana. Surface oil samples were taken one meter into the marsh in February 2011. All high oiled sites in Bay Batiste were contaminated with Macondo 252 oil (oil from the Deepwater Horizon oil spill, 20 April–15 July 2010). The results suggest that there is a threshold where soil parameters change dramatically with a relatively small increase in oil concentration in the soil. Heavy oiling weakens the soil, creating a deeper undercut of the upper 50 cm of the marsh edge, and causing an accelerated rate of erosion that cascades along the shoreline. Our results demonstrate that it could take at least 2 yr to document the effects heavy oiling has had on the marsh shoreline. The presence of aboveground vegetation alone may not be an appropriate indicator of recovery.

Keywords: wetland, Deepwater Horizon oil spill, salt marsh, Louisiana, erosion

1. Introduction

Salt marshes have long been considered to be resilient to natural and anthropogenic disturbances (Gedan *et al* 2011). However, other coastal ecosystems have shifted to alternative stable states induced by human activity (Jackson *et al* 2001), leading to a decline in the services they supply (McClenachan 2009, zu Ermgassen *et al* 2013). Originally thought to provide no benefit in their natural state, wetlands have been altered by humans for centuries through levees, impoundments, canals, and diversions (Salinas *et al* 1986). As natural hydrologic regimes are modified, the coast becomes more vulnerable to land loss (Deegan *et al* 1984), potentially pushing a marsh's erosional resilience past a threshold where one perturbation could result in cascading effects (van de Koppel *et al* 2005).

The 20 April 2010 Deepwater Horizon (DWH) oil spill at Mississippi Canyon Block 252 killed 11 people, injured 17, and released approximately 5 million barrels of oil into the Gulf of Mexico 66 km from the Louisiana coastline from 20 April to 15 July. It was the largest spill event in US history and the fifth largest in the world. Of all five of the Gulf of Mexico states, the oil released disproportionately affected Louisiana. Roughly 1000 km of Louisiana's shoreline was oiled, equaling about 60% of the total oiled shoreline in the Gulf of Mexico (Owens *et al* 2011). 7 times larger than the Exxon Valdez oil spill, the DWH spill had the potential to cause significant damage to Louisiana's coastal habitats.

The rate of land loss in Louisiana was significant before 2010 (42.92 km² yr⁻¹ from 1985 to 2010; Couvillion *et al* 2011), and so the threat of increased erosion rates from the oiling in 2010 are an additional concern. There are many contributing factors to the disappearance of Louisiana's coastal marshes, both anthropogenic (e.g., oil and gas canals (Bass and Turner 1997), sediment supply (Tweel and Turner 2012, Blum and Roberts 2009)) and natural (e.g., subsidence;



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Blum and Roberts 2009). Major episodic disturbances, such as the DWH spill, can contribute to the short- and long-term yearly estimates of land loss, but, depending on the time series analyzed, may not be recognized as the source of elevated erosion. Chronic exposure to oil can cause increased shoreline erosion (Hershner and Lake 1980), and results from a small sample size of heavily oiled marsh sites ($n = 3$) after the DWH spill indicate that exposure to oil elevated marsh shoreline erosion rates (Silliman *et al* 2012). Although thought to be tied to salt marsh plant health, the mechanisms controlling this increased erosion are poorly understood.

The below- and aboveground biomass of *Spartina alterniflora*, the dominant salt marsh grass in coastal Louisiana salt marshes, helps to increase marsh resistance to erosion. The belowground plant biomass provides erosion protection for the shoreline edge via root strength and mass (Gabet 1998, Micheli and Kirchner 2002). The aboveground stems of *S. alterniflora* trap sediment by slowing tidal and wave energy, which can help maintain a sustainable marsh elevation as sea level continues to rise (Redfield 1972, Stumpf 1983, Li and Yang 2009). Marsh loss potentially will be enhanced if the marsh plants' health is compromised.

The results of laboratory and field studies on the effects of oil on *S. alterniflora* growth have shown that high amounts of oil can have significant negative impacts on both above- and belowground production (Li *et al* 1990, Lin and Mendelsohn 1996). The most severe impacts tend to occur when the oil is applied during the growing season of the plants (spring and early summer) (Alexander and Webb 1985, Webb 1994) and when the oil persists in highly organic soils (Pezeshki *et al* 2000). NOAA reported DWH oil entering Louisiana's coastal marshes in June 2010 (NOAA 2010a). This timing coincides with the most intense growth of *S. alterniflora*, giving the oil the potential to impart substantial damage to the vegetation and, in turn, cause a significant increase in shoreline erosion. Lin and Mendelsohn (2012) reported significant initial aboveground dieback of heavily oiled *S. alterniflora*, while Silliman *et al* (2012) documented significantly greater erosion at three heavily oiled sites following the DWH spill event, which is attributed to a decrease in aboveground plant cover.

Here, we provide a trajectory of the rate of erosion and recovery over 2 yr in low and high oiled coastal marshes in southeast Louisiana. We also investigated some of the physical and biological mechanisms driving the variation in the erosion rates among sites and over time.

2. Materials and methods

2.1. Site selection

We established 30 closely located *Spartina alterniflora* dominated salt marsh sites on 12–13 November 2010 along the northern edge of Bay Batiste in the southeast Louisiana estuary of Barataria Bay (figure 1). November 2010 was approximately six months after the DWH oil first reached the barrier islands at the entrance to the bay (Port Fourchon 11 May 2010, and on Raccoon Island on 13 May 2010). There are a total of 10 groups of 3 sites each. The 3 sites within

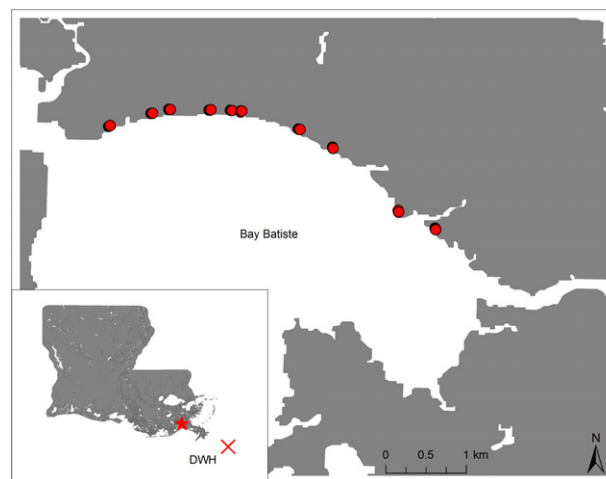


Figure 1. Locations of 30 sampling sites along Bay Batiste's northern edge. There is a cluster of 3 sites, 10 m apart, at each of the 10 red dots.

each group of 3 were 10 m apart. NOAA SCAT shoreline survey maps (NOAA 2010b) were used to incorporate a range of oiling, with the non-oiled sites acting as the control or reference group. The sites were subsequently separated into high and low oiled categories (see below).

2.2. Field measurements

We collected a surface oil sample within the top 5 cm of soil, one meter from the marsh edge, from each site in February 2011, August 2012, and September 2012. The samples were analyzed by gas chromatography/mass spectrometry for petroleum hydrocarbons including the normal and branched saturated hydrocarbons (from C10 to C35), the one- to five-ringed aromatic hydrocarbons and their C1–C4 alkyl homologs, and the hopane and sterane biomarkers. All GC/MS analyses use an Agilent 7890A GC system configured with a 5% diphenyl/95% dimethyl polysiloxane high-resolution capillary column (30 m, 0.25 mm ID, 0.25 μ m film) directly interfaced to an Agilent 5975 inert XL MS detector system. The data are reported in Turner *et al* (2013, in revision). The samples containing oil were identified as MC252 oil by comparing key markers of petroleum hydrocarbons in the sample to MC252 source oil (Overton *et al* 1981, Iqbal *et al* 2008).

The polycyclic aromatic hydrocarbon (PAH) concentrations were used as the proxy for oil exposure in the analyses discussed here. The average PAH concentrations in these samples and others demonstrate no statistically significant decline from September 2010 to October 2012 (Turner *et al* 2013, in revision).

The sites were divided into high and low oiled sites. The 13 sites where the PAH concentration was $<1000 \mu\text{g kg}^{-1}$ were considered 'low' or 'background' oil sites and used as the control or reference sites. The 17 sites where the PAH concentration was $>1000 \mu\text{g kg}^{-1}$ were placed in the high oiled category.

The horizontal shoreline erosion, soil strength, per cent cover of *S. alterniflora*, and marsh edge overhang were sampled at each site. We placed permanent PVC poles 1.5 and 4.5 m in a straight line into the marsh from the shoreline edge. Edge erosion and gain were measured 5 times using these poles as reference points. Soil strength measurements were taken in November 2010 and August 2012. Soil strength and per cent cover of *S. alterniflora* were measured at the 1.5 m pole until the edge eroded past this location; after this occurred, the readings were taken 1.5 m into the marsh from the marsh edge. A shear vane was used to measure soil strength in a 1 m profile, at 10 cm intervals using a Dunham E-290 Hand Vane Tester. The per cent cover of live *S. alterniflora* was estimated for a 0.5 m × 0.5 m plot. The portion of the intact marsh overhanging a missing layer beneath was measured as an indicator for future erosion potential. We measured marsh overhang roughly 15 cm below the top of the marsh surface.

2.3. Energy calculation

We calculated the wave energy at each site to test the hypothesis that the erosion rates we measured were due to normal physical stress (i.e., wave and wind force) at these specific locations and that they were not due to the exposure to oil. Because of their close proximity, we calculated wave energy for each of the 10 groupings of 3 sites rather than the individual sites, with the middle site in each grouping serving as the location for the estimation of fetch. The PAH concentrations and total erosion were also averaged for the 3 sites in each grouping of 10. Wind speed and direction data were downloaded from the Louisiana State University (LSU) AgCenter website for a weather station located in Port Sulfur, LA at 10 m-height and 13 km from our study sites (LSU 2012). The data interval is for April 2007 to June 2011. We used SAS (SAS 9.3, SAS Institute, Inc. 2012) to calculate the per cent frequency the wind blew from each direction and the associated average wind speed with this direction. We used fetch lengths calculated using ArcInfo10.0 (Environmental Systems Research Institute), together with the wind speed and direction data and an online software program (USGS 2007), to estimate wave height and period for each of the eight major directions (N, NE, E, SE, S, SW, W, NW) at each of the 10 locations for the prevailing wind patterns. A water depth of 2 m was used for all sites since Bay Batiste has a relatively shallow homogeneous depth. These parameters were then used to calculate a weighted average 'wave energy' at each site based on the per cent frequency of time the wind blew from each direction.

2.4. Bay Batiste shoreline change

We used vectorized aerial imagery to investigate historical changes to the morphology of the Bay Batiste shoreline. Imagery was compiled at four time intervals between 1956 and 2012 from the USGS Earth Explorer (1956, 1972, and 1998) and TerraServer (2012). Pixel sizes were 2.2 m (1956), 3 m (1972), and 1 m for all other years, and data

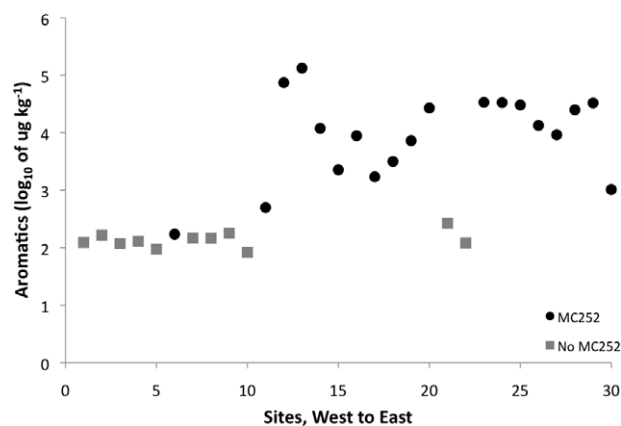


Figure 2. Oil concentration (log aromatics) at each of the 30 sites. The black circles indicate the presence of DWH oil; gray squares designate the presence of oil from other sources.

were projected in North American Datum 1983 UTM Zone 16 North. Images were classified into a bi-color raster to distinguish between vegetation and water, and then converted to vector data using ArcScan, which is an extension of ArcInfo.

2.5. Statistical methods

We used an ANCOVA to determine if oil concentrations or exposure time had significant effects on erosion, per cent cover, and overhang. We used a two-way ANOVA for the same independent variables once the oil concentrations were split into categories (high and low) and tested for interactions between the categories and time. Separate covariances were used to meet the assumptions. Student's *t*-tests were used to detect differences in the soil strength because it was not measured at every site visit. Student's *t*-tests and multiple regression analysis were also used to determine if there were differences in the energy calculations for the oil categories and the range of oiling at the 10 groupings. A Tukey's HSD post hoc test was used to test for significant differences, which were at $\alpha < 0.05$, unless otherwise indicated. SAS 9.3 (SAS Institute, Inc. 2012) was used for all statistical analyses.

The data are archived in the Coastal Waters Consortium webpage at the Louisiana Universities Marine Consortium (www.lumcon.edu) and also with the Gulf of Mexico Research Initiative Information and Data Cooperative (<http://griidc.gomri.org>, doi:10.7266/N7TD9V7W).

3. Results

3.1. Oil concentration

The PAH concentrations varied from 82 to 133 000 $\mu\text{g kg}^{-1}$ across all samples at the 30 sites, with approximately 150× higher concentrations when DWH oil was present. Every site contained some oil, but all of the sites with high oil concentrations were contaminated with oil from DWH (MC252) (figure 2). Only two of the sites in the low category had MC252 oil. The sites contaminated with MC252 oil, and

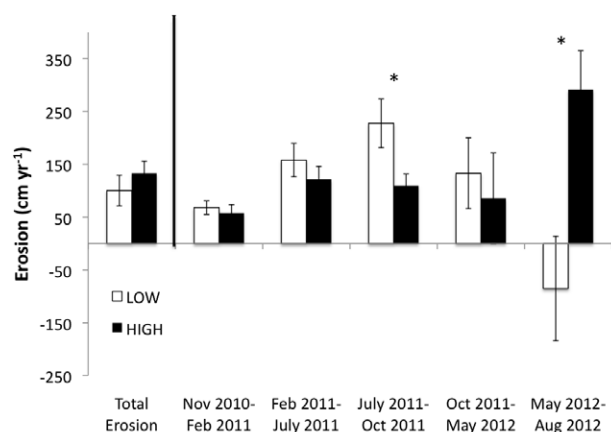


Figure 3. Erosion rate per year for high and low oil sites in each time period. Positive erosion values indicate erosion, whereas negative values indicate accretion. The error bars are ± 1 SE. A '*' indicates significant difference ($p < 0.01$).

Table 1. Concentration of PAH ($\mu \pm 1$ SE) in sites contaminated with Macondo oil (MC252) and those without (No MC252), and low ($< 1000 \mu\text{g kg}^{-1}$) and high ($> 1000 \mu\text{g kg}^{-1}$) oiled categories.

	Sample size	PAH concentration ($\mu\text{g kg}^{-1}$)
MC252	19	$23\,648 \pm 7405$
No MC252	11	143 ± 15
High	17	$26\,390 \pm 8030$
Low	13	172 ± 30

those in the high oil category, had average PAH concentrations more than 150 times higher than those without MC252 oil and those in the low oil category (table 1).

3.2. Erosion rates

The erosion rate for the entire sampling time period (November 2010–August 2012) was lower for the low oil sites (100 cm yr^{-1}) than for the high oil sites (133 cm yr^{-1}), but did not differ significantly ($F_{(1,65)} = 0.85$; $p = 0.36$). Despite no significant differences in the total erosion rate between the two oil categories, an interesting pattern emerged when the erosion rates of high and low oil sites were analyzed with sampling time added as an additional variable. Both time ($F_{(4,35)} = 5.68$; $p < 0.01$) and category \times time ($F_{(4,35)} = 3.62$; $p = 0.01$) were significant variables in the ANCOVA. The low oil sites had a greater rate of erosion for the first four time periods (November 2010–May 2012). However, the erosion rate was significantly greater at the high oil sites in the last time period (May 2012–August 2012; figure 3).

The erosion rate accelerated at the low oil sites for the first three time periods. There was also greater overall erosion at the low oil sites than at the high oil sites during this time period, culminating in a significant difference in the erosion rate in the third time period. After October 2011, however, the low oil sites' erosion rate decreased and lateral accretion began in May 2012, as the high oil sites experienced increased erosion rates.

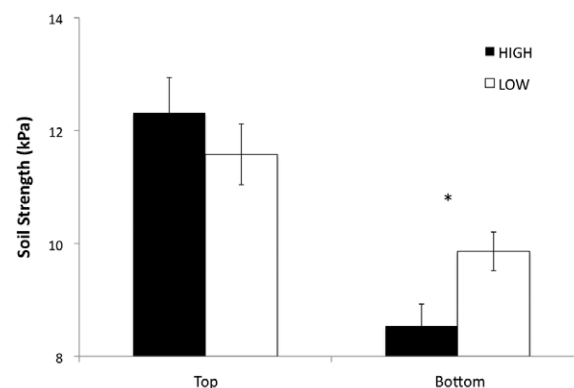


Figure 4. Soil strength in the top layer (0–50 cm) and bottom layer (60–100 cm) of high and low oil sites in November 2010. The error bars are ± 1 SE. A '*' indicates significant difference ($p < 0.01$).

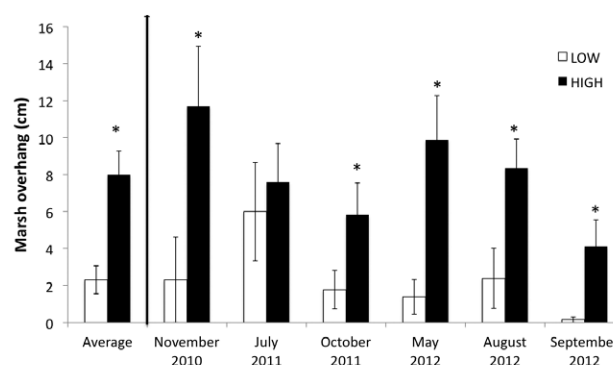


Figure 5. Overhang of the marsh (cm) for each time period in high and low oil sites. The error bars are ± 1 SE. A '*' indicates significant difference ($p < 0.05$).

3.3. Soil strength

The November 2010 soil strength measurements in the top layer (0–50 cm) of soil were not significantly different in the two categories ($p = 0.19$). The soil strength in the bottom layer of soil (60–100 cm), however, was significantly weaker in the high oil sites than in the low oil sites ($p = 0.008$; figure 4). There were no significant differences between the high and low oil sites in the August 2012 readings.

3.4. Overhang

The amount of marsh overhang showed a consistent relationship between low and high oil sites throughout the sampling period. The high oil sites had a significantly greater overhang than the low oil sites ($p < 0.03$ for all) for all time periods except July 2011 (figure 5).

3.5. Aboveground plant cover

There was no significant difference in per cent cover of *S. alterniflora* between the high and low oil sites, for any of the time periods except for October 2011. The per cent cover of *S. alterniflora* was marginally significantly higher ($p = 0.09$)

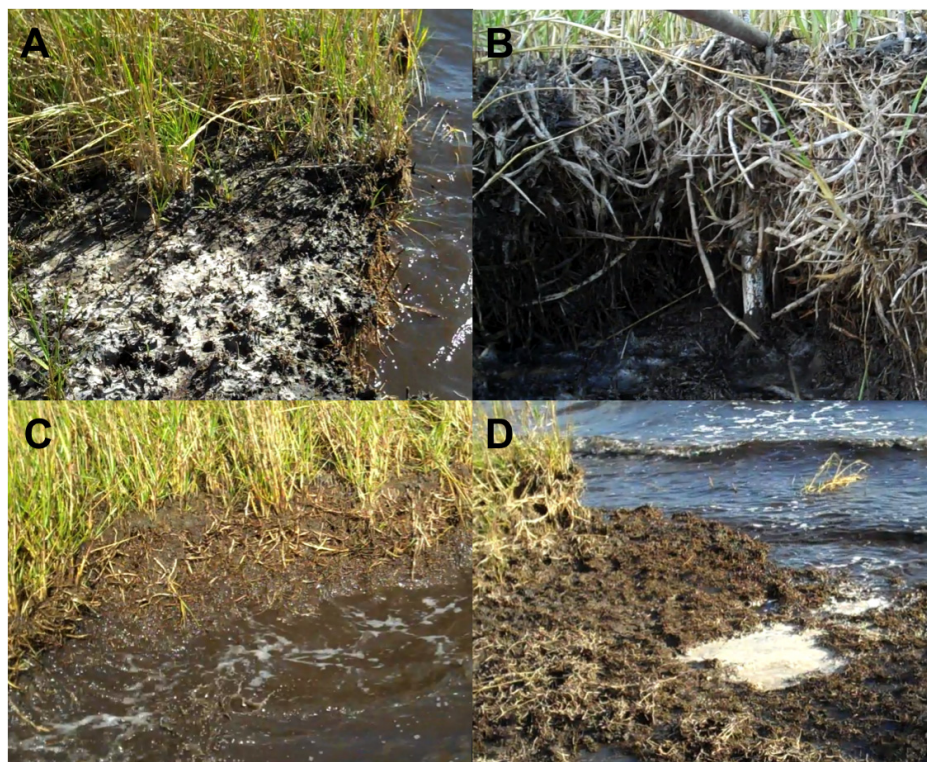


Figure 6. Photographs of marsh erosion process due to oil induced overhang. (A) Oil coating on top few millimeters of marsh platform. (B) Overhang of oiled marsh edge. (C) Initial collapse of marsh when overhang becomes too large. (D) Slumping of large portion of oiled marsh with dead stems still visible.

at high oil sites (39% cover) compared to low oil sites (26% cover). There was a significant time effect for both oiling levels due to the seasonality of aboveground cover.

3.6. Energy

The wave energy at the low oil sites ($n = 3$) was not significantly different ($p = 0.103$) than at the high oil sites ($n = 7$). The erosion rate at the low oil sites was lower (59 cm yr^{-1}) than at the high oil sites (116 cm yr^{-1}), although not significantly different ($p = 0.62$). There was no significant relationship between erosion rate and wave energy ($R^2 = 0.063$; $p = 0.48$).

4. Discussion and conclusion

4.1. Vegetation

Our data suggests that, while the impact to *S. alterniflora* marshes from the DWH oil may not be evident from the presence or absence of aboveground cover or even in the top layer of soil, heavy oiling significantly weakened the bottom layer of soil. The weaker bottom layer of soil, coupled with the same, or slightly stronger, soil in the top layer, has produced the dramatic overhang pattern observed at the high oil sites (figure 6). Coastal marshes attenuate wave energy from storms and reduce shoreline erosion (Gedan *et al* 2010, Shepard *et al* 2011) and soil strength can be directly linked to plant belowground biomass (Turner 2011, Micheli and

Kirchner 2002). The compromised integrity of the marsh should, therefore, eventually lead to greater erosion at the high oil sites, which is what we observed in 2012. Since there was no difference in the wave energy at low and high oil sites, the increased erosion documented at the high oil sites is most likely due to oiling and not background conditions.

The weakening of the soil at the high oil sites can lead to direct erosion via increased susceptibility to daily wave and tidal action. Concomitantly, reducing the belowground biomass may lower the marsh's ability to sustain an elevation that matches the high relative sea level rise ($\sim 1 \text{ cm}$) of the Gulf of Mexico (Penland and Ramsey 1990). There is a direct relationship between the accumulation of organic matter and the vertical accretion of the marsh, which allows for the marsh surface to keep up with sea level rise (Turner *et al* 2004). The slow land loss caused by sea level rising at a greater rate than the marsh can accrete, a possible consequence of heavy oiling, demonstrates the difficulty in accurately and completely quantifying the damages associated with exposure to oil.

The mechanisms behind the oil's impact on vegetation are varied and complex. The effects can be physically or chemically induced and the severity may vary depending on where the oil lands (plant stems, plant leaves, or soil) (Pezeshki *et al* 2000). Previous studies looking at the effect of oil on marsh vegetation have mainly focused on the aboveground growth as an indicator of stress (DeLaune *et al* 1979, Lin and Mendelssohn 1996), although a few of these studies have documented increased aboveground

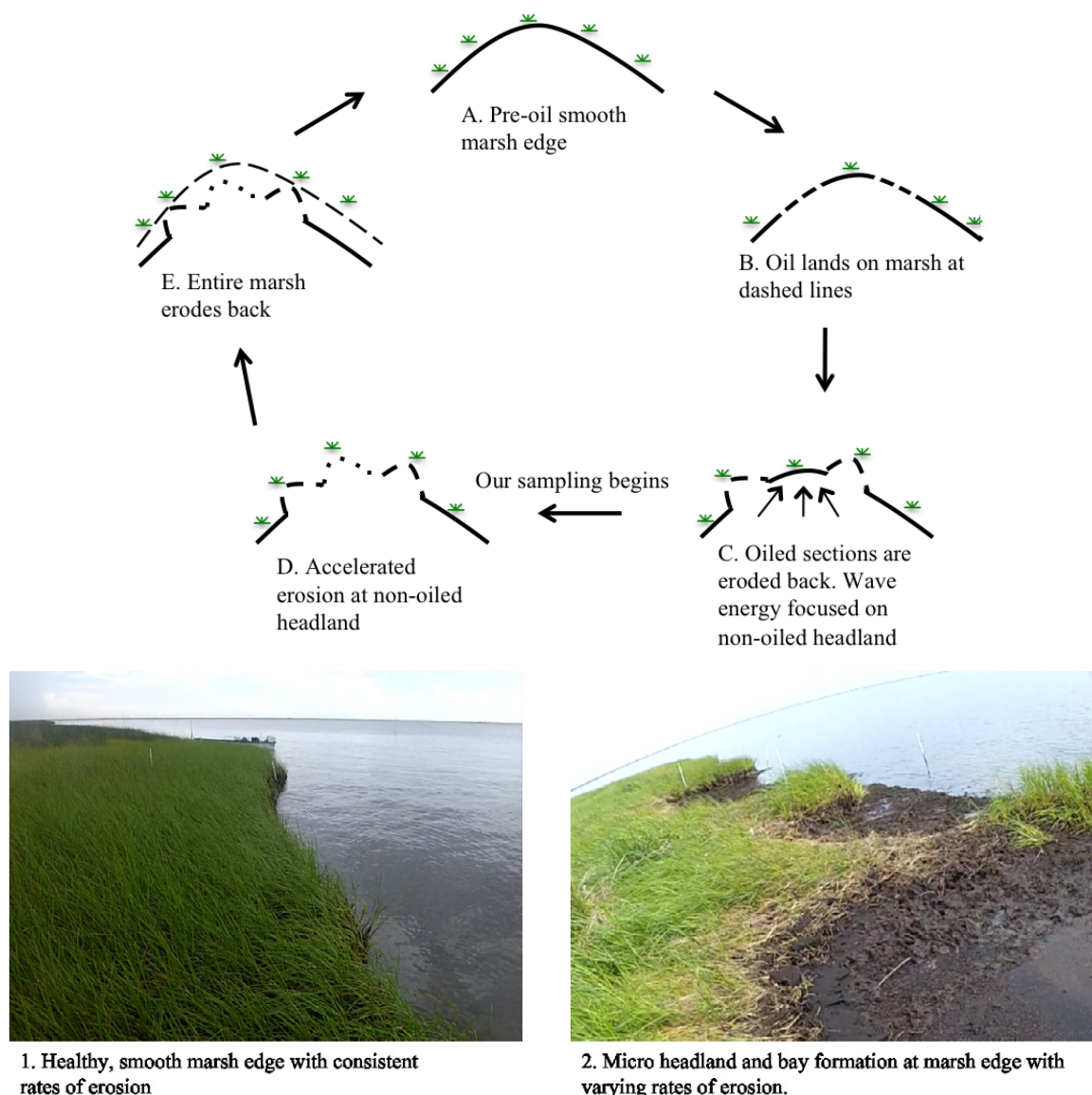


Figure 7. Schematic of oil landing on portions of marsh edge. (A) Marsh before oil lands (picture 1). (B) Oil lands on certain portions of marsh and erodes those sections (dashed line). (C) This erosion causes headlands to form (picture 2), which, in turn, are exposed to wave energy from more directions. (D) Erosion rate accelerates at non-oiled section (dotted line). (E) Equilibrium is reached and erosion rates slow to background rates until next event. We think we began sampling our sites between (C) and (D).

growth with small oil additions (Hershner and Moore 1977, Li *et al* 1990). Nutrient additions to salt marshes have also elevated aboveground cover, but have simultaneously decreased belowground growth and soil strength at deeper depths (Turner 2011). A similar effect of growth stimulation, leading to decreased soil strength, may be in play at the high oil sites. Increased oil may also accelerate microbial activity in fresh marsh soil (Nyman 1999). This could potentially increase the rate of decomposition, perhaps fueling the weakening of the soil and large undercuts in the high oil areas. We saw no significant difference in aboveground cover for our low and high oiled sites, yet we documented differing erosion rates and soil parameters. Although we are unsure of the exact processes involved in a cause-and-effect manner, our data provides evidence that quantifying belowground health

up to one meter deep may be needed to accurately evaluate the impact that heavy oiling may have on coastal marshes.

4.2. Erosion over time

Although we did not observe a significant difference in total erosion rates between the high and low oil sites, focusing on the changing erosion rate of the individual time intervals reveals an interesting pattern. The NOAA SCAT oiling surveys observed heavy-to-moderate oil reaching the majority of the northern shore of Bay Batiste by the end of June 2010 (NOAA 2010a). However, we did not conduct our first site visit until five months after the initial oiling. There is a high likelihood the heavy oil may have impacted the vegetation before we arrived, leading to a possible missed erosion event at the highly oiled sites. A large erosion event in certain areas

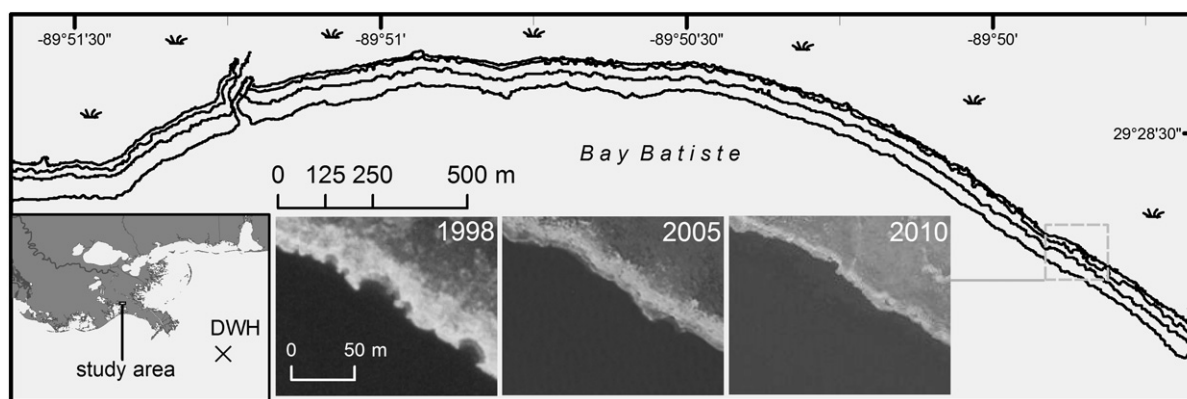


Figure 8. Historical shorelines of Bay Batiste since 1956. The study sites span the entire range of the coastline pictured.

of the shoreline would have left those that did not erode as micro-headlands. As headlands, these areas would now be receiving more energy than those that had eroded, causing an accelerated rate of erosion (figure 7).

The erosion rate increased for each of the first three time periods at the low oil sites, suggesting that they were headlands when we first sampled in November 2010. Roughly 1.5 yr after the initial heavy oiling of Bay Batiste, the erosion began decreasing at the low oil sites and increasing at the high oil sites, suggesting that the low oil sites are no longer headlands. If we truly did miss an erosion event at the heavily oiled sites, then not only has the oil caused increased erosion at the locations it came ashore, but also at the adjacent marsh as the shoreline was eroded to a new equilibrium.

The erosion feedback mechanism has been seen over short periods of time in Delaware marshes as well, where erosion rates varied for clefts and necks (Schwimmer 2001). This data may be an indicator of the mechanism by which the marsh shoreline is eroding in Louisiana. As a section of marsh is weakened and subsequently erodes, the erosion of the adjacent marsh accelerates, causing a cascading effect of increased erosion along the Louisiana shoreline. Historical shoreline imagery for Bay Batiste shows that the gentle arc of the northern shoreline has remained constant despite significant retreat since at least 1956 (figure 8). After the 1998 hurricane season, small inlets and micro-headlands formed (figure 8, 1998). The shape of the original coastline returned as the headlands retreated in response to increased wave energy (figure 8, 2005 and 2010). Rather than eroding at a steady rate each year, the shoreline may be lost in segments of rapid erosion after major disturbances.

The sequential erosion demonstrated within our dataset may suggest that coastal marshes are not as resilient to large disturbances as previously thought. The timescale of monitoring has a large effect on whether a system is considered resilient or not. This concept has been extensively studied in fisheries as the idea of shifting baselines (Jackson *et al* 2001). Shifting baselines along an erosional coast may imply a shoreline that looks the same pre- and post-disturbance, suggesting that no erosion occurred as a direct result of the disturbance. If the shoreline were observed before the oil spill and again 2 yr after, then the equilibrium

of form demonstrated in Bay Batiste could have been seen as resiliency. In actuality, erosion accelerated at both high and low oiled sites and the current marsh edge may now be more vulnerable to increased erosion via weakened soil strength. Previous models suggest that after an initial disturbance occurs at the marsh edge, the increased erosion may cause a cascading effect that can be visible years after (van de Koppel *et al* 2005). The evidence from the first 2 yr post oil spill suggest this may be the case at our sites.

Our results demonstrate that it could take at least 2 yr to document the detrimental effects heavy oiling has had on the marsh shoreline. The results from other studies indicate that heavily oiled marshes are eroding faster than non-oiled marshes over the first 18 months post-spill (Silliman *et al* 2012). This observation is consistent with Alexander and Webb's (1987) findings of shoreline erosion occurring after 16 months, and continuing through 32 months, at heavily oiled locations after an oil spill on the Texas coast. Despite our sites appearing recovered as measured by changes in plant cover, we have documented increased erosion at the high oil sites 26 months post-spill and elevated erosion at the low oil sites roughly 12–18 months post-spill. Silliman *et al* (2012) found erosion rates at heavily oiled locations leveled off to reference rates by 1.5 yr. However, we have not seen the same recovery at our sites. Our larger sample size and wider range of oil levels may be driving the differences documented in recovery and resilience of the salt marshes post-disturbance. The full extent of the DWH oil's impact to marsh erosion rates may not be evident for many years; the weakening of the soil and possible decrease in organic matter accumulation could lead to submergence of the marsh edge as relative sea level increases faster than the marsh can vertically accrete soil.

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